Air-Sea Momentum Coupling and Radar Response at High Winds

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LONG-TERM GOALS

To determine the changes in air-sea frictional drag and normalized radar cross-section at high winds and to investigate the root causes of regime changes in the momentum coupling and the radar response.

OBJECTIVES

- To verify preliminary laboratory experiments showing "saturation" of the drag coefficient and of the radar backscatter at high winds.
- To use the high precision wave follower and an Elliott style pressure probe to measure the pressure very near the water surface in strong winds.
- To measure the surface pressure and slope of wind-generated and paddle-generated waves in high wind conditions.
- To measure the full wavenumber-frequency spectrum in high wind conditions.
- To determine the mechanism for momentum and energy transfer to the waves in various wind speed regimes and thus to elucidate the air-sea coupling mechanisms in high winds.
- To measure the radar cross-section for both HH and VV polarizations at C-band under high wind conditions and to determine the relationship between capillary-gravity wave properties and radar response in these conditions.

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APPROACH

Numerical models of hurricane intensification typically employ bulk coefficients of momentum, heat and moisture to parameterize the driving and dissipative effects of the air-sea coupling. Bulk coefficients based on field measurements typically cover the range of wind speeds of 5 to 20 m/s. (Much above this range the data is too sparse to produce reliable estimates of statistically variable turbulence quantities.) In this range the data show a linear increase of the bulk coefficient for momentum (the drag coefficient), while the heat and moisture coefficients appear to be constant. Extrapolation of the bulk estimates to higher wind speeds leads to the conclusion that typical tropical warm oceans cannot sustain hurricanes of the strength observed, i.e., categories 4 and 5 hurricanes would not occur. This raises the question of the appropriateness of the application of existing bulk models to high winds. Perhaps the drag coefficient "saturates" at high winds or the heat and moisture coefficients increase significantly.

Donelan and Pierson (1987) predicted the saturation of Bragg scattering contributions to σ_o at high winds and various recent comparisons with buoys seem to show this effect in VV polarized σ_o values. In addition a preliminary test in our Air-Sea Interaction Saltwater Tank (ASIST) confirms saturation of σ_o at high winds.

We propose to employ the wind-wave facility (ASIST) at the Rosenstiel School to explore the effect of high winds on the air-sea momentum coupling. The ASIST facility has a working section of 1 m x 1 m x 15 m. The water depth can be selected up to 0.5 m and at this maximum depth the (centerline) wind speed can be selected between 0 and 30 m/s (equivalent to greater than 100 knots at 10 m height). At this maximum speed wave breaking is intense and the tops of the wave crests are blown into spume. Waves may also be created in any chosen pattern with a programmable hydraulic wave maker. In addition, a current of up to 0.5 m/s may be generated in either direction. The working section is constructed of acrylic so that optical measurements may be made anywhere along the 15 m fetch. This facility was acquired through DURIP grant number N00014-98-1-0261.

Several approaches to measuring the total momentum transfer will be employed:

1. Direct Reynolds stress measurements using hot-film anemometry. This approach is limited to winds in which the concentration of spray in the air is low.

2. Momentum balance on the air side including the horizontal gradient of pressure, wall stress on the walls and ceiling, changes in the velocity profile.

3. Momentum balance on the water side including the set-up of the surface, horizontal pressure gradient in the air ("inverted barometer effect") bottom stress.

4. Velocity profile measurements using the "law of the wall" to deduce the stress.

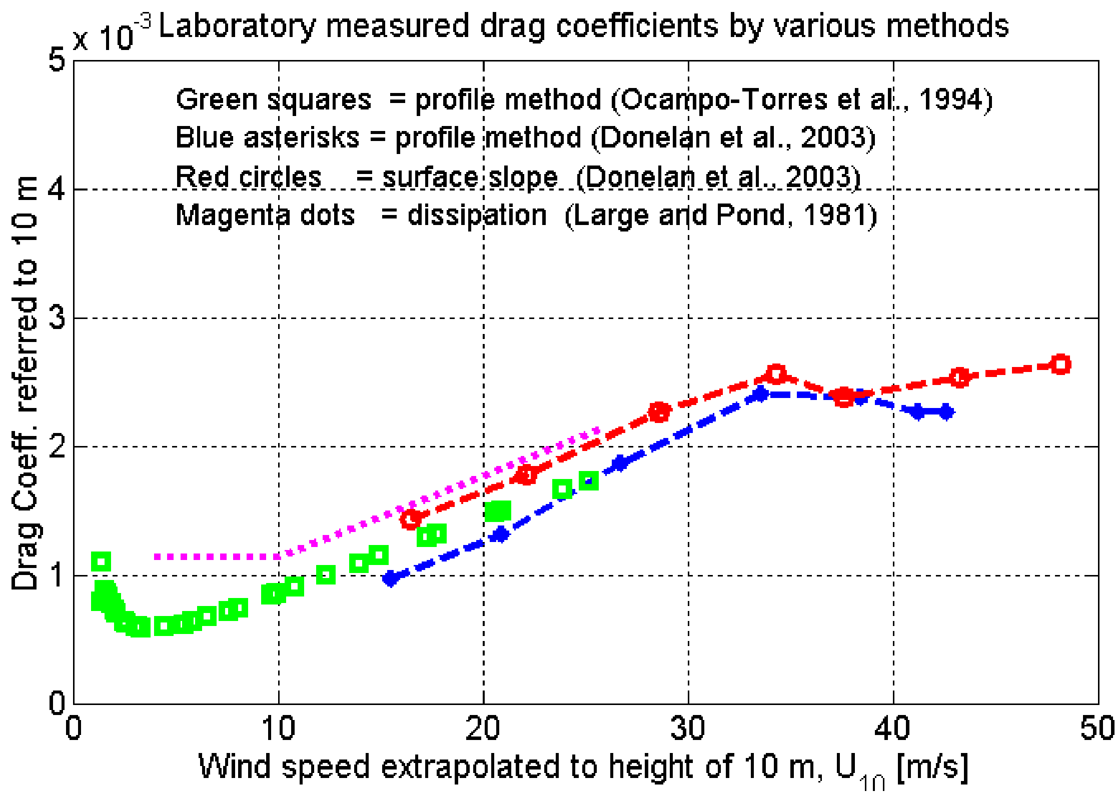

Fig.1. Measured drag coefficients in high winds.

Figure 1 shows the drag coefficients estimated via the latter two methods. In addition data from another laboratory tank are added to cover the lower wind speeds. In all cases the wind speed and drag coefficients are extrapolated to the standard 10 m height. The measured drag coefficients display the characteristic reduction with wind speed at very low winds corresponding to smooth flow, i.e., viscous drag. Above 5 m/s the effects of form drag (rough flow) become apparent and the drag coefficient shows a steady increase with wind speed. The conventional view (e.g., Large and Pond, 1981) suggests that the drag coefficient keeps on increasing with wind speed. Our preliminary results, shown in Figure 1, are indicative of a rapid "saturation" of the drag coefficient at about 35 m/s. There seems to be a "regime change" in the aerodynamic characteristics of the flow at these high speeds. Preliminary indications are that the continuous (observed) breaking of the largest waves leads to a quasi-permanent separation bubble in the wake of the breaking crests so that the external flow does not penetrate to the troughs and instead flows over a surface that appears to aerodynamically smoother than it is in the absence of separation. We may call this regime "sheltered flow".

Of course, these far reaching inferences are drawn on the basis of laboratory data and there are reasons why oceanic drag coefficients may differ in magnitude if not in form. In order to be able to infer the drag characteristics of the natural ocean surface in these high winds we need to understand the way in which the flow regime changes and why. The best way to elucidate this problem is to measure the detailed flow structure near the surface in these strong winds. In particular we will measure the pressure near the surface in a wave following frame. The product of surface pressure with surface slope is the form drag, which is the dominant source of drag in strong winds.

The approach to measuring the direct pressure/slope correlation is as follows:

The wave follower will maintain an “Elliott” pressure probe (Elliott, 1972) at a selected fixed distance above the surface. The Elliott probe will be back-flushed with a steady stream of air to avoid wetting of the pressure ports from spray. The slope of the surface beneath the “Elliott” probe will be measured with a triplet of Laser Elevation Gauges (LEGs) arranged in an equilateral triangle of side 1 cm. These gauges use line scan cameras to detect the transition from dark (air) to light (water) of a vertical beam of fluorescence induced (in the fluorescein added to the water) by a laser beam directed vertically through the bottom of the tank. The line scan cameras scan downward at a scan rate of 250 Hz and associated electronic circuitry detects the dark/light transition, i.e., the surface. The triplet of Laser Elevation Gauges yields both the vector slope of the surface (differences) and the mean surface elevation (sum). The latter is the command signal for the wave follower. Most measurements of the pressure near the surface are correlated with surface elevation measurements and so nothing can be said about the directional properties of the form drag on waves. In our approach, the local surface slope vector correlated with the surface pressure yields the distribution of form drag with direction.

The wave follower will also carry an x-hot-film anemometer in order to measure the wind speed and stress profiles in a frame of reference relative to the surface.

The approach to measuring σ_o is as follows:

- The radar response (σ_o) will be measured with our in-house dual polarized C-Band scatterometer at various incidence angles. The scatterometer is mounted on a rotating arm so that its range is kept constant as the incidence angle is changed. The radar radiates a patch of the surface about 10 cm in diameter. The radiated patch is in the center of the area imaged by a 2-D imaging slope gauge and just downwind from the triplet of laser elevation gauges. The imaging slope gauge covers an area of 30 cm by 20 cm (downwind by crosswind) with a resolution of 0.5 mm by 0.8 mm. It will therefore allow us to view the Bragg scatterers in detail and also to be able to correlate them with the slopes of the longer wind waves and any paddle waves we introduce. The imaging slope gauge has a maximum sampling rate of 120 Hz.

The approaches to measuring the wavenumber-frequency spectrum are as follows:

- The Wavelet Directional Method (WDM) of Donelan et al. (1996, JPO) will be used with the triplet of LEGs to yield the full 3-D wavenumber-frequency spectrum. In addition the fine temporal resolution of the method allows us to locate scatterers on the various phases of the dominant wave and especially their relation to the whitecaps.

- The 2-D imaging slope gauge allows us to measure the full wavenumber-frequency spectrum by direct application of 2-D FFTs. This makes it a fundamental tool in the characterization of the short gravity and capillary waves that are crucial to understanding radar remote sensing.

Synthesis: The pressure/slope product will yield the direct wind input to all waves longer than about 1 cm. This limitation is related to the size of the Elliott probe (1 cm diameter). Calculations indicate that most of the stress is carried by waves longer than this. Thus we can integrate the pressure/slope cospectrum over the entire wave number range to determine the total “form drag”. The difference of the total stress and the form drag we will assign to “viscous drag”. The form of the pressure pattern on

the surface will yield important clues to the existence of a "sheltered flow" regime and to a fuller understanding of the drag on the ocean in high winds.

Having both the carefully calibrated radar response and full information on the scatterers, we expect to be able to explore the response of σ_o in strong winds as well as its root causes. The several methods of characterizing the surface texture will allow us to identify the source of anomalies in Bragg scattering models including 2-scale models. Frequency-wavenumber spectra will allow us to separate bound and free waves and to identify scattering associated with the strong nonlinearities that are produced in high winds. Finally, our Digital Particle Image Velocimeter will be used to identify the spray and spume droplets and to assess their effect on the radar response.

WORK COMPLETED

This project is a new start late in FY03. Efforts so far have been devoted to preparing the new data acquisition system (DAQ) and to testing the miniaturized Elliott pressure probe.

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